Scenario analysis of a low-carbon transition of the EU industry by 2050: Extending the scope of mitigation options

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Keywords

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Abstract

Industry accounts for about 25 % of EU final energy demand and uses gas, electricity, coal, and oil as the dominant energy carriers. This makes the sector critical for the achievement of European climate goals. The EU Roadmap for moving to a competitive low carbon economy in 2050 states a potential of 83 to 87 % emission reductions in industry by 2050. Several analyses show that industry is unlikely to meet this target without a major change in the policy frame. Our contribution presents two alternative transition scenarios for the EU28 that achieve a reduction in GHG emissions of more than 85 % by 2050 compared to 1990 for the industrial sector. The scenarios are based on the bottom-up simulation model FORECAST, which allows simulating technological change with a high level of technological detail also considering policy instruments. The transition scenario contains mitigation options including energy efficiency, fuel switch to RES, CCS, power-to-heat, secondary energy carriers based on RES, innovative production technologies and new products, material efficiency, substitution and circular economy elements. Thus, the scope of mitigation options is very broad, particularly compared to the scenario calculations that were conducted to support the EU Low Carbon Roadmap, which is mainly based on CCS for the industrial sector. Results show that RES and energy efficiency have huge potentials towards decarbonisation. But also changes in production structure giving way to new innovative technologies like renewable hydrogen based direct reduction in the steel industry or low carbon cement types are needed. This scenario reflects a radical change to be achieved in less than 35 years. Even if many mitigation options will be rolled out in large quantities only after 2030, policies need to be in place soon to drive this transition. A potential policy mix towards implementation of the modelled transition scenario is discussed at the end and compared to current policies in place in the EU.

Introduction

The industrial sector[1] accounts for about 25 % of EU final energy demand and uses gas, electricity, coal, and oil as the dominant energy carriers (see Figure 1). This high share in final energy demand is mainly due to energy-intensive industries such as iron and steel or the chemical sector. Within these industries, specific energy-intensive products/processes (e.g. steel, cement, ammonia) are particularly relevant for the future achievement of European climate targets. Some sectors such as the paper industry already use a high share of electricity and biomass. In general, however, industry still needs to make substantial further efforts to reduce the use of fossil fuels in the next decades. With 31 %, the **non-metallic minerals** sector is the biggest contributor of direct industrial CO_2 emissions (see Figure 1[2]). It is dominated by the production of cement clinker, which emits about 0.5 tonnes of process CO_2 emissions per tonne of

1. The definition of industry in this article follows final energy definitions and excludes the refinery sector as well as electricity onsite generation.

2. Energy-related emissions are linked to the definition of Eurostat's final energy balance (incl. coke ovens). Process-related emissions are calculated using a bottom-up approach for individual products. With this approach, emissions from coke and coal consumption for oxygen steel production are fully accounted for as energy-related emissions.

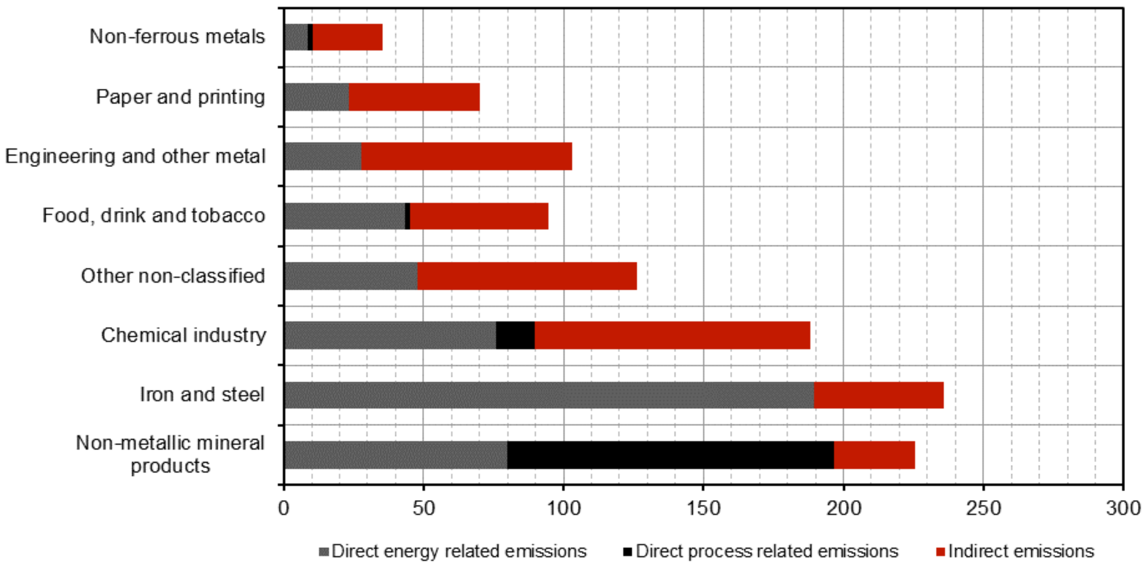

Figure 1. EU 28 industrial emissions in Mt CO_2-eq. by subsector (2015). Source: FORECAST.

clinker produced. Other CO_2-intensive products of the non-metallic minerals sector include lime, the calcination of dolomite/magnesite, glass, bricks and ceramics. The production of pig iron or steel in the **iron and steel** industry was responsible for around 30 % of direct industrial CO_2 emissions in 2015. The main emissions are from the (technically required) use of coal and coke in blast furnaces. In addition, **chemical** processes such as ammonia, ethylene or methanol production contribute to industrial emissions, making the chemical industry the third biggest emitter of direct CO_2 emissions.

In terms of end-uses, most industrial GHG emissions are from high-temperature process heat, either in the form of steam or hot water, or from the direct firing of various types of furnaces. These two end-uses have shares of 23 % and 45 % of total direct GHG emissions, respectively (see Figure 2[3]). The high temperatures and the specific requirements of furnaces limit the use of renewable energies here to biomass or secondary energy carriers. Process-related emissions account for about 21 % of all direct emissions. It is technically difficult or even impossible to mitigate them in the processes used at present. Finally, even the provision of space heating is responsible for 11 % of GHG emissions, something that should not be overlooked when assessing industrial energy demand and CO_2 emissions.

This article focuses on direct (energy and process) emissions in industry. In a future sustainable energy system, we assume that electricity is supplied by renewable sources and is therefore CO_2-neutral. Reducing process emissions appears to be a particular challenge for the industrial sector, as these types of emissions can only be reduced by radical changes in the production process, product mix or by the use of carbon capture and storage (CCS).

3. Energy-related emissions are linked to the definition of Eurostat's final energy balance (incl. coke ovens). Process-related emissions are calculated using a bottom-up approach for individual products. With this approach, emissions from coke and coal consumption for oxygen steel production are fully accounted for as energy-related emissions.

The EU Roadmap for moving to a competitive low carbon economy in 2050 (COM 2011) has set a target of 83 to 87 % emission reductions in industry by 2050. Several analyses show that industry is unlikely to meet this target without a major change in the policy frame. The following contribution present a transition scenario for the EU28 that achieves a reduction in GHG emissions of more than 85 % by 2050 compared to 1990 for the industrial sector using a variety of mitigation options including energy efficiency, fuel switch to RES, CCS, power-to-heat, secondary energy carriers based on RES, innovative production technologies and new products, material efficiency, substitution and circular economy elements.

Methodology – the model used

The following scenario calculations are conducted using the bottom-up energy demand model FORECAST-Industry (for detailed information see www.forecast-model.eu and the listed literature there). Compared to the other sectors, the industrial sector shows the highest degree of heterogeneity with regard to technologies and energy users (i.e. companies). This poses a huge challenge to a bottom-up model, which mainly focuses on large homogenous groups of energy uses/ energy services. At the same time, the number of energy uses should not be too high, as gathering input data is very time and resource intensive.

Thus, the structure of the industrial sector module also reflects this heterogeneity and the data availability in the industrial sector. Selected energy-intensive processes are explicitly considered, while other technologies and energy-using equipment are considered in the form of cross-cutting technologies modelled similarly across all sub-sectors. The model is a bottom-up simulation model, which reflects the fact that the investment decisions are modelled according to real-life behaviour of investors. Thus, in contrast to often used optimization models FORECAST does not calculate the energy system based on least system cost. Instead, barriers to the adoption of energy efficient technologies are considered. Considering barriers and sub-optimal behaviour of investors also allows including various policy instruments such as standards, taxes and subsidies. Following data availability and heterogeneity also different approaches are used in the various modules to simulate technology diffusion. These range from diffusion curves to vintage stock models and discrete choice simulation.

Figure 3 shows the simplified structure of FORECAST-Industry. Starting with a macroeconomic module that translates scenario information into physical drivers of energy demand considering inter-sectoral and intra-industrial structural change, changes in material strategies as well as circular economy aspects, it comprises the following main sub-modules to calculate future energy demand:

1. **Energy-intensive processes**: this module presents the core of the bottom-up quantity structure of FORECAST. 76 individual processes/products are considered via their (physical) production output and specific energy consumption (SEC). The diffusion of about 200 individual energy efficiency measures (EEMs) is modelled based on their payback period (Fleiter et al. 2013; Fleiter et al. 2012).
2. **Space heating and cooling**: we use a vintage stock model for buildings and space heating and cooling technologies. The model distinguishes between offices and production facilities for individual sub-sectors. It considers construction, refurbishment and demolition of buildings as well as construction and dismantling of space heating technologies. The investment in space heating technologies such as natural gas boilers or heat pumps is determined based on a discrete choice approach (Biere et al. 2014).
3. **Electric motor systems and lighting:** these cross-cutting technologies (CCTs) include pumps, ventilation systems, compressed air, mechanical equipment, cold appliances, other motor appliances and lighting. The module captures the individual units as well as the entire motor-driven system including losses in transmission between conversion units. The electricity demand of the individual CCTs is estimated based on typical shares by sub-sector. The diffusion of EEMs is modelled similarly to the approach used for process specific EEMs.
4. **Furnaces:** energy demand in furnaces is a result of the bottom-up estimations from the module "energy-intensive processes". Furnaces are found across most industrial subsectors and are very specific to the production process. Typically, they require heat on a very high temperature level. While EEMs for individual furnaces are modelled in the module "energy-intensive processes" the module on furnaces simulates price-based substitution between energy carriers. The method is based on a random utility model (logit model). The model is calibrated using revealed preferences data gained from regression analysis of historic time series (a similar method is used by Kesicki, Yanagisawa 2015).
5. **Steam systems:** the remaining process heat (<500 °C) is used in steam systems throughout most subsectors. The module comprises both the distribution of steam and hot water as well as its generation. As very little information is available about the performance of existing steam distribution systems, we assume exogenous efficiency improvements for each scenario based on available literature. Steam generation is included in the optimization of central heat and power generation to allow for capturing the interdependencies between the two sectors. This link allows considering the benefits of electricity from CHP generation and power-to-heat as a way to use electricity in times of high wind and solar generation.

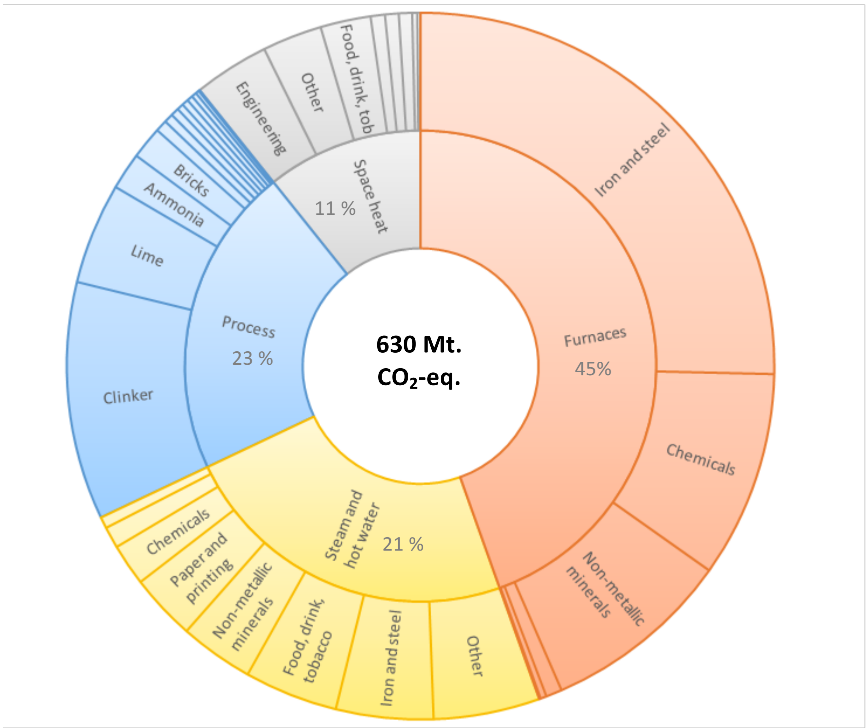

Figure 2. EU 28 industrial emissions in Mt CO_2-eq. by subsector (2015). Source: FORECAST.

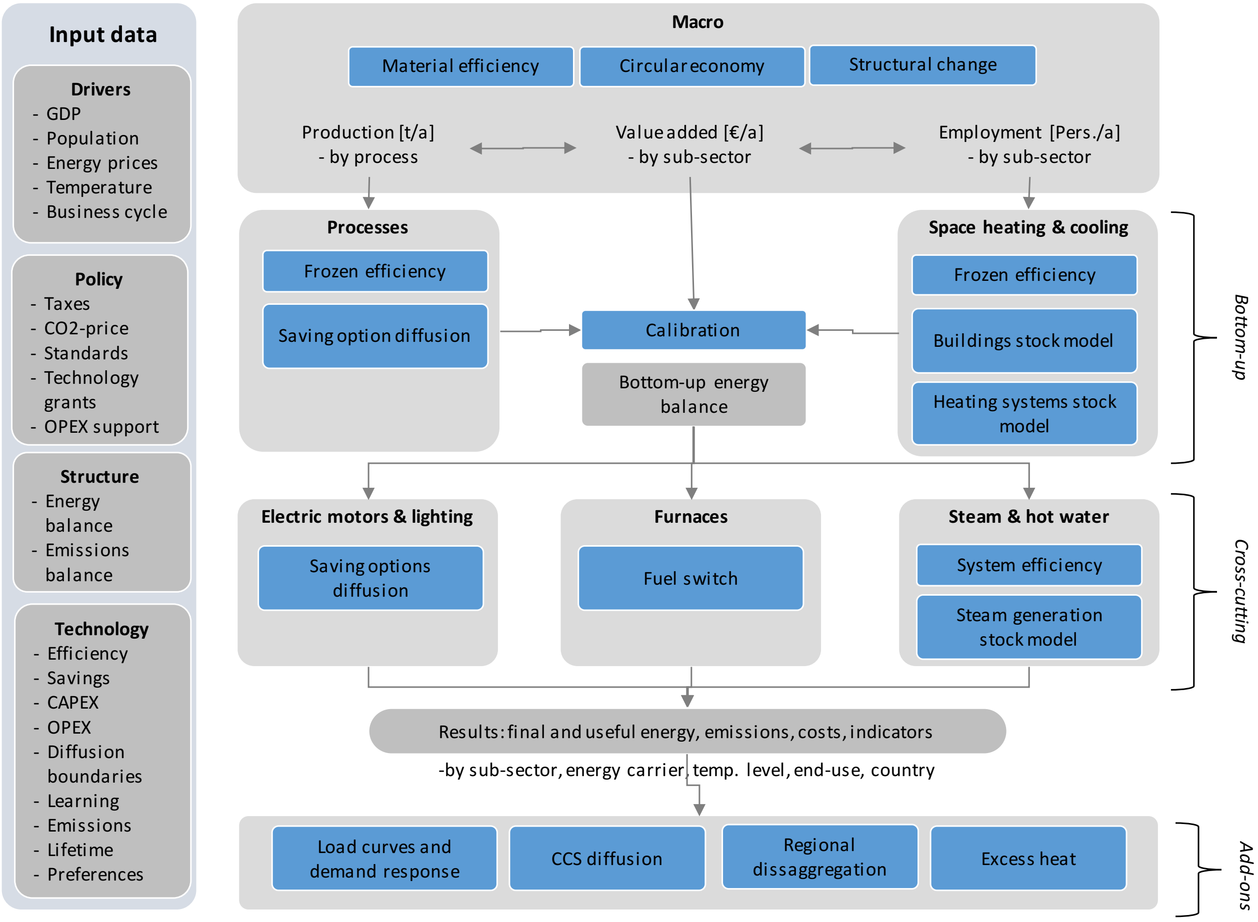

Figure 3. FORECAST-Industry model overview. Source: Fraunhofer ISI.

All modules described above consider 8 individual sub-sectors by country for the EU28 using the definition of the Eurostat energy balances. The model FORECAST is based on a hierarchical structure: 76 energy-intensive processes are considered and each is allocated to one sub-sector. CCTs are also considered by sub-sector as share of electricity demand of the respective sub-sector. The energy demand of CCTs and processes can overlap. E.g. the electricity demand of a paper machine mainly comes from electric motors to provide mechanical energy. This is accounted for in the process "paper" as well as in the individual CCTs like pumps, machine tools and other electric motors. Both do present a different perspective on the same demand. EEMs are considered for processes as well as CCTs. The former include EEMs related to the process characteristics and the latter EEMs that are of a horizontal nature like replacing electric motors. Energy demand of processes and CCTs changes when EEMs diffuse through the technology stock.

Scenario definition and input data

For the model-based analysis, we define three different scenarios.

- A *Reference scenario (REF)*, which reflects the effects of current policies on the future energy system and serves as a benchmark to compare the more ambitious scenarios.
- The *Transition scenario including CCS in industry (TRANS-CCS)* describes an industrial decarbonisation pathway aiming to reduce European industrial greenhouse gas emissions in 2050 using carbon capture and storage technologies.
- The *Transition scenario including innovative process technologies in industry (TRANS-IPT)* describes an industrial decarbonisation pathway aiming to reduce European industrial greenhouse gas emissions in 2050 using innovative production technologies and new products but excluding CCS.

The **macroeconomic framework** data (gross domestic product, gross value added, population) for the model-based analysis is taken from the European Reference Scenario 2016 (Capros et al. 2016) and stays the same across scenarios. The reason for this assumption is the better comparability of changes in policy parameters and assumptions between scenarios. The same holds true for the assumptions on **wholesale fossil fuel price** development (coal, gas, oil), which are also based on the European Reference Scenario 2016 and held constant between scenarios.

The macroeconomic framework data shown in table indicates that industry is expected to continue growing until 2050. However, energy-intensive industries like the iron and steel industry and the non-ferrous metals industry grow below industrial average (<1 % p.a.) in the scenarios. An exception is the chemical industry, which is growing at a slightly above average rate (probably caused by growth in the less energy intensive pharmaceutical industry compared to the energy-intensive basic chemicals) and the non-metallic minerals sector (including cement production). Stronger growth is to be expected in non-energy-intensive sectors like engineering (incl. vehicle construction) and the food industry, which reflects structural change in industry towards less-energy-intensive branches. Energy carrier prices are increasing up to 2050. Between scenarios only **electricity prices** differ, assuming a stronger increase for the policy cases compared to the reference case due to the higher share of renewables expected/necessary in the energy system.

Both transition scenarios contain mitigation options including energy efficiency, fuel switch to renewable energy sources (RES), power-to-heat, secondary energy carriers based on RES, material efficiency, substitution and circular economy elements which are not considered in the REF scenario. Technology assumptions are the same in both transition (TRANS) scenarios with regard to the performance of energy supply. Compared to the reference case there is financial support for RES granted in both TRANS scenarios and additional efforts in material strategies are undertaken. Both scenarios depict an innovative environment where ambitious exploitation of energy efficiency measures and incremental energy efficiency improvement is taking place. However, in the TRANS-CCS scenario the use of existing equipment in combination with carbon capture and storage technologies act as main mitigation option while in the TRANS-IPT scenario a paradigm shift in industry is expected allowing completely new process technologies (e.g. low carbon cement or renewable hydrogen based direct reduced steel) to enter the market.

INCREMENTAL CHANGES IN PROCESS TECHNOLOGIES

Incremental process improvements are assumed in both scenarios, TRANS-CCS and TRANS-IP. They can be used as add-on options to existing process equipment and imply only limited changes in the production process. They do not affect the resulting product. However, some technologies are classified in-between incremental and radical changes and might be included in both categories. One example for the **steel industry** is **top gas recycling** in which the CO_2 is removed from the blast furnace's top gas by means of a separation system and useful components such as carbon and hydrogen are recovered. The reducing gas is fed back into the reactor, which reduces the coke rates compared to a conventional blast furnace. (EUROFER 2014; Pardo und Moya 2013) Another example for the steel industry is **near-net-shape casting**.

Oxyfuel combustion can be used in the **glass industry** by burning the fuel with more oxygen instead of combustion air in the current furnace atmosphere. This leads to increased efficiency and reduced fuel consumption. Oxyfuel combustion requires smaller heat recovery systems and can reach higher temperatures without emitting NO_x as a by-product. (British Glass 2014). **Batch preheating** is another option to reduce fuel demand in the glass and ceramics industry. Drying the paper web is the most important energy-consuming process in paper mills. This leads to a need for **new drying technologies** that use energy more efficient and consequently reduce CO_2 emissions. Fleiter et al. (2012b) discussed such new drying techniques and examples include impulse drying or condensing belt drying.

Table 1. Macroeconomic framework assumptions.

EU 28	CAGR '15-'50
Population (in millions)	0.1 %
Gross domestic product (GDP) (in 000 M€13)	1.5 %
Gross value added (GVA) industry (in 000 M€13):	*1 %*
Iron and steel	*0.3 %*
Non-ferrous metals	*0.5 %*
Chemicals	*1.1 %*
Non-metallic minerals	*0.9 %*
Paper	*0.8 %*
Food, drink, tobacco	*1.1 %*
Engineering	*1.3 %*
Textiles	*-1.2 %*
Other	*0.9 %*

Source: Capros et al. 2016.

Other options in the paper industry include **black liquor gasification** and **enzymatic pre-treatment**.

Significant energy efficiency gains in aluminium production can be expected from the use of stable **inert anodes** in combination with stable **wettable cathodes** reducing energy consumption for electrolysis and anode manufacturing as well as CO_2 emissions. (Moya et al. 2015). **Magnetic billet heating** – replacing fuel-fired furnaces by induction-melting furnaces and thereby electricity – is another option in the **non-ferrous metals industry**.

FUNDAMENTAL CHANGES IN PROCESS TECHNOLOGIES

Radical innovative process technologies are considered major mitigation option in the TRANS-IPT scenario assuming market entry mainly in/after 2030. Depending on the sector and production process, the market entry and the maximum CO_2 saving potential as well as the costs can differ significantly.

In the **iron and steel industry renewable hydrogen** (RES H2) can be used for the **direct reduction** of crude steel. Hydrogen replaces the carbon from fossil fuels (coal and coke) in the metallurgical process, but at the same time, large quantities of electricity are needed for its production. (EUROFER 2017; Voestalpine AG et al. 2017; SSAB AB 2017). Consequently, direct reduced steel based on hydrogen will only lead to substantial CO_2 savings if the needed electricity is produced from renewable energy sources. In the TRANS-IPT scenario, a complete substitution of the basic oxygen furnace route steel production via RES H2 direct reduced steel is assumed until 2050.

In the **cement industry**, **new binders** based on alternative raw materials substituting limestone can significantly reduce CO_2 emissions. Such new binders reduce both: process-related (less/no decarbonation) and energy-related emissions (lower process temperatures, lower demand for thermal energy) compared to conventional cement (clinker) production. Different concepts with different technologies and materials are developed. Examples for new products/processes are Aether, Solidia,

Table 2. Scenario assumptions overview.

Type of instrument	Instrument	REF	TRANS-CCS	TRANS-IPT
Subsidies	Financial support of high efficiency cross-cutting technologies	–	Increase in total financial support and particular (successful) focus on system optimization.	Increase in total financial support and particular (successful) focus on system optimization.
	Financial support of energy audits for SMEs	–	Increasing support and number of audits. The model implementation is done in an aggregated way via changed assumptions on investment decision thresholds.	Increasing support and number of audits. The model implementation is done in an aggregated way via changed assumptions on investment decision thresholds.
Instruments based on prices and quantities	Emissions trading (EU ETS)	EU ETS remains as designed in the 3rd trading period. Price is exogenously assumed and increases to 88 Euros/t CO_2 in 2050. Companies do not anticipate increasing prices.	EU ETS remains as designed in the 3rd trading period. Price is exogenously assumed and increases to 150 Euros/t CO_2 in 2050. Companies anticipate increasing prices ten years ahead, thus assuming a stringent and well communicated commitment to the EU ETS.	EU ETS remains as designed in the 3rd trading period. Price is exogenously assumed and increases to 150 Euros/t CO_2 in 2050. Companies anticipate increasing prices ten years ahead, thus assuming a stringent and well communicated commitment to the EU ETS.
	CO_2 tax	No particular CO_2 tax. Only existing energy taxation.	A CO_2 tax is implemented for the non-ETS sector to incentivize fuel switch to low-carbon fuels. The tax equals the ETS CO_2 price. Companies anticipate increasing prices five years ahead.	A CO_2 tax is implemented for the non-ETS sector to incentivize fuel switch to low-carbon fuels. The tax equals the ETS CO_2 price. Companies anticipate increasing prices five years ahead.
Strategies	Material strategies and circular economy	Slow increase in recycling rates based on historic trends. No additional material efficiency of substitution efforts is taking place.	Increases in material efficiency, substitution and recycling rates assumed.	Increases in material efficiency, substitution and recycling rates assumed.
	Incremental efficiency improvement	Energy efficiency progress according to current policy framework and historical trends.	Faster diffusion of **incremental process improvements** (BAT & INNOV ≥ TRL 5*).	= TRANS-CCS
	Fundamental process improvement	–	–	**Radical process improvements** (INNOV ≥ TRL 5*).
	Fuel switching to RES	Fuel switching driven by energy prices and assumed CO_2-price increase	Financial support for RES technologies: Fuel switching to biomass and electricity (<500 °). **Use of existing equipment** (no radical changes in industrial processes technologies).	High financial support for RES technologies: Stronger fuel switching to biomass, power-to-heat and power-to-gas technologies compared to TRANS-CCS. **Radical changes in industrial process technologies** take place (e.g. switch to hydrogen).
	Carbon capture and storage	–	CCS for major energy-intensive point sources	–

Source: Fleiter et al. 2016 and own assumptions.

** TRL = Technology readiness level.*

and Celitement. The following groups of new binders – defined according to their CO_2 mitigation potential – are included in the scenario analysis: less carbon cement (-30 %), low carbon cement (-50 %), low carbon cement (-70 %). In the TRANS-IPT scenario, low carbon cement sorts using new binders will substitute 50 % of conventional ordinary Portland cement production until 2050.

In the **chemical industry,** the use of **renewable hydrogen** (**RES H2**) is an innovative mitigation option to reduce CO_2 emissions from the production of basic chemicals. In the illustrated cases for ammonia and methanol, large quantities of electricity are needed for hydrogen synthesis that substitutes the conventional fossil combustion reaction. (Dechema 2017). Consequently, – as it is the case for direct reduced steel based on hydrogen – these processes can only lead to substantial CO_2 savings if the needed electricity is provided from renewable energy sources. The possible reduced need for feedstock cannot be depicted in the model system shown and is therefore not considered in the TRANS-IPT scenario. In the TRANS-IPT scenario, RES H2 for ammonia and methanol production will substitute conventional ammonia and methanol production up to 50 % in 2050.

In the **glass industry**, **renewable electricity** can be used instead of natural gas to reduce future CO_2 emissions and increase thermal efficiency. The technology is already available on industrial scale but yet not wide spread (British Glass 2014; Cerame Unie 2013). Mostly smaller furnaces currently apply this process in which the conductivity of molten glass increases and allows the use of resistant heating (Fleiter et al. 2016b). The TRANS-IPT scenario assumes up to 50 % increase of RES electrification in the glass industry in 2050.

CARBON CAPTURE AND STORAGE

Carbon capture and storage is the major mitigation option considered in the TRANS-CCS scenario, which assumes its market entry in 2030. CCS is used for selected point sources that were identified based on the amount, intensity and purity of emissions. Depending on the sector and production process, different CO_2 capture techniques are applied. They all have different advantages and disadvantages and vary in terms of technical maturity, as discussed in the following.

Due to the high process-related CO_2 emissions for clinker burning, CCS is a highly discussed mitigation option in the **cement sector**, and alternative designs are feasible including post-combustion capture, oxyfuel combustion with CO_2 capture, pre-combustion and carbon looping. **Post-combustion** seems to be an option that could be implemented in the near future – a few pilot and demonstration plants already exist. The technical risk of this option is comparatively low, but it requires large amounts of heat. **Oxyfuel combustion** is another option that could be used to retrofit existing kilns, but it requires significant structural changes to the core units in the cement plant (Kuramochi et al. 2012). Options like oxyfuel combustion and **carbon looping** technologies are not yet mature and require more research and development. In the frame of the EU H2020 project LEILAC another CCS technology based on **direct separation** is developed for the lime industry having the advantage of not requiring large amounts of additional energy for the CO_2 capture as a pure stream of process-related emissions from calcination is generated by separating it from fuel combustion.

Various alternative production routes for substituting conventional integrated steelmaking are discussed in the **iron and steel industry** including add-on CO_2 capture, process-integrated CO_2 capture and smelting reduction. There are two different ways to apply **CO_2 capture** as an **add-on** technology to the blast furnace: either as direct capture from the BF gas (capture rate ~50 %) or indirect capture after the conversion of CO to CO_2, which yields higher capture rates. The **top-gas recycling blast furnace** (ULCOS-BF, IGAR) is another possible option for **process-integrated CO_2 capture.** The technology is currently being tested in a pilot plant (Luleå, Sweden) and may be implemented in the medium-term as it can also be used for conventional blast furnace retrofits. Another possible option is the use of **smelting reduction technologies** in combination with CO_2 capture technologies. The **COREX, FINEX** or **HIsarna** processes are examples for this option. In the HIsarna process, input carbon is fully oxidized resulting in high possible capture rates (~80 %). The first two processes are already commercially available but have not yet become widespread in Europe; the HIsarna process is currently also in the pilot stage level (Ijmuiden, Netherlands) (Eurofer 2014; Eurofer 2017; Pardo u. Moya 2013, Kuramochi et al. 2012). Currently (launched in 2016), there is only one large-scale CCS project for the iron and steel industry (Mussafah, Abu Dhabi) (IEA 2017, Global CCS Institute).

MATERIAL STRATEGIES

The transition scenarios (TRANS-CC and TRANS-IPT) feature material efficiency improvements, product substitutions, trends to higher gross value added, re-use and trends to secondary production. In contrast, the reference scenario (REF) does not include material efficiency improvements or production substitutions at all and trends to higher gross value added and secondary production here are based on historical trends only. Secondary production routes comprise production based on recycled materials (e.g. recycled paper, electric arc furnace steel production or secondary aluminium production). The increase in secondary products is based on domestically available resources (e.g. domestic scrap availability). Net exports are assumed to remain on a similar level as today. The shift from oxygen steel to electric steel, for example, takes place faster in the TRANS scenarios and represents a more ambitious path in line with the maximum scrap availability (Herbst et al. 2014) compared to the reference case.

Results

Results show that RES and energy efficiency have huge potentials towards decarbonisation. In addition, changes in production structure giving way to new innovative technologies renewable hydrogen based direct reduction in the steel industry or low carbon cement types as well as CCS are needed. GHG emissions are continuously decreasing in all scenarios from 2015 to 2050 as shown in Figure 4.

In total EU28 GHG emissions decrease from 630 Mt CO_2 in 2015 to 190 Mt in the TRANS-CCS scenario and 192 Mt in the TRANS-IPT scenario compared to 560 Mt in the reference case. This reflects a reduction of 70 % in both scenarios compared to 2015. Process related emissions account to 134 Mt CO_2 in 2015 and decrease to 104 Mt in the TRANS-CCS and 76 Mt

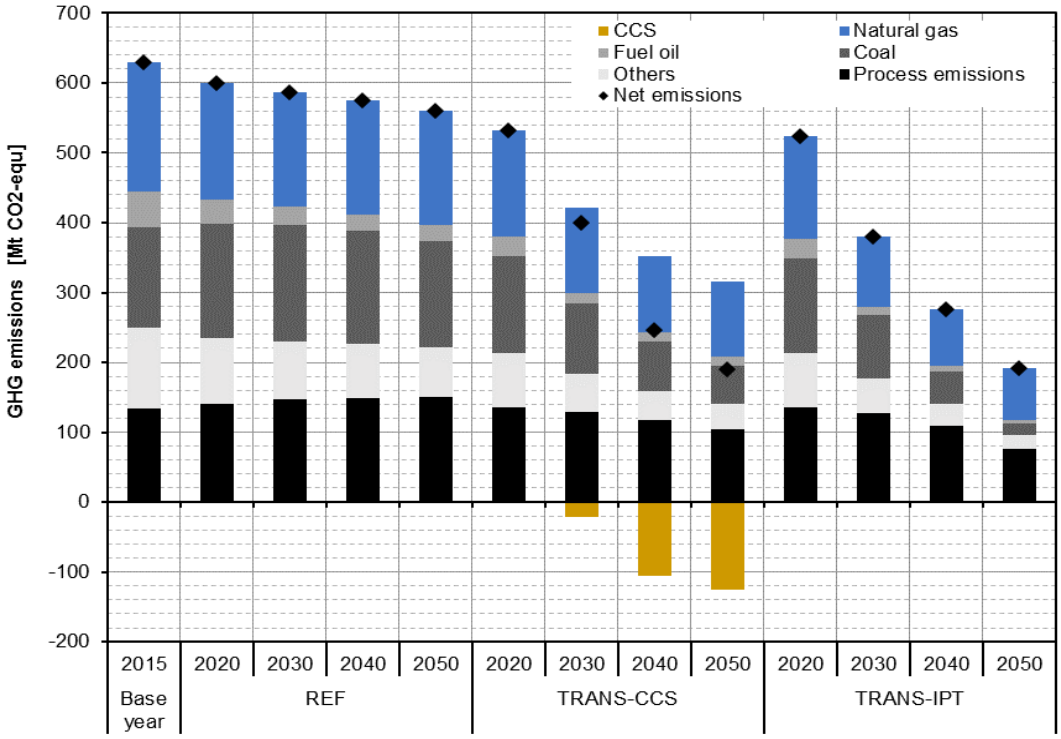

Figure 4. EU 28 GHG emissions by scenario (2015–2050).

in the TRANS-IPT scenario. In the REF scenario process emissions increase to 151 Mt by 2050. In the TRANS-CCS scenario approximately 125 Mt energy and process related emissions are stored via CCS (CCS bar in Figure 4). The slow reduction of process-related emissions in this scenario is explained by the fact that they are related to the total production of clinker/cement, lime, ammonia and methanol, which does not change substantially. In the TRANS-IPT fundamental changes in process technologies take (e.g. Ammonia H2, low carbon cement) place which lead to significantly lower process emissions.

In the reference scenario (REF) industrial final energy demand (FED; Figure 5) for the EU28 is only slightly decreasing as efficiency effects are nearly equalled out by activity effects (e.g. gross value added growth). Among others, the process shift in the iron and steel industry from primary (fossil-fuelled basic oxygen furnace) to secondary (electricity-fuelled electric arc furnace) production has led to lower fuel uses in 2050 accompanied by an increase in electricity. These structural changes in the steel industry also lead to a reduction of future CO_2-emissions in the REF scenario as the less energy-intensive scrap, electricity based production route reduces process, and energy related CO_2-emissions for steel production. In the transition scenarios, FED is also decreasing in both scenarios until 2050, however a lot slower than GHG emissions (Figure 4, Figure 5).

Nevertheless, the TRANS scenarios experience a faster reduction of FED than the REF scenario. Until 2030 FED is more or less the same between transition scenarios, however after 2040 there is a slightly higher FED in the scenario including fundamental changes in process technologies TRANS-IPT. In total, FED is "only" 17 % lower in the TRANS-IPT scenario in 2050 than in the REF scenario (-28 % in the TANS-CSS). In general, renewable energies substitute a large part of industry's demand for natural gas in the TRANS-IPT scenario and coal and oil are replaced almost completely – particularly in the areas of fuel demand for low-temperature heat and the use of waste heat in combination with heat pumps. However, two contrary trends can be observed in the transition scenarios:

- First, the conventional demand for electricity decreases due to integrated process improvements (energy efficiency) and fuel switching to alternative renewable energy sources like biomass. The use of biomass nearly doubles in 2050 compared to 2015 in the TRANS-CCS scenario (464 TWh in 2050). In the TRANS-IPT scenario, the increase is even more pronounced: +166 % to 658 TWh in 2050.
- Second, large volumes of renewable electricity will be necessary due to electrification measures (e.g. electric melting processes) and (onsite) hydrogen production for industrial uses, e.g. 98 TWh for hydrogen-based ammonia synthesis in 2050 or 211 TWh for direct reduced steel via RES-H2 in 2050 in the TRANS-IPT scenario.

Thus, results from the available industry transition scenarios indicate a role for CCS and fundamental changes in industrial production processes in some sub-sectors as the remaining CO_2 emissions from the reference scenario (today's policies) indicate the need for substantially more CO_2 abatement.

Summary and conclusions

The transition scenarios calculated (TRANS-CCS and TRANS-IPT) for the European industry sector have been aimed to achieve at least an 85 % reduction of greenhouse gas emissions compared to 1990. The transition scenarios for industry show

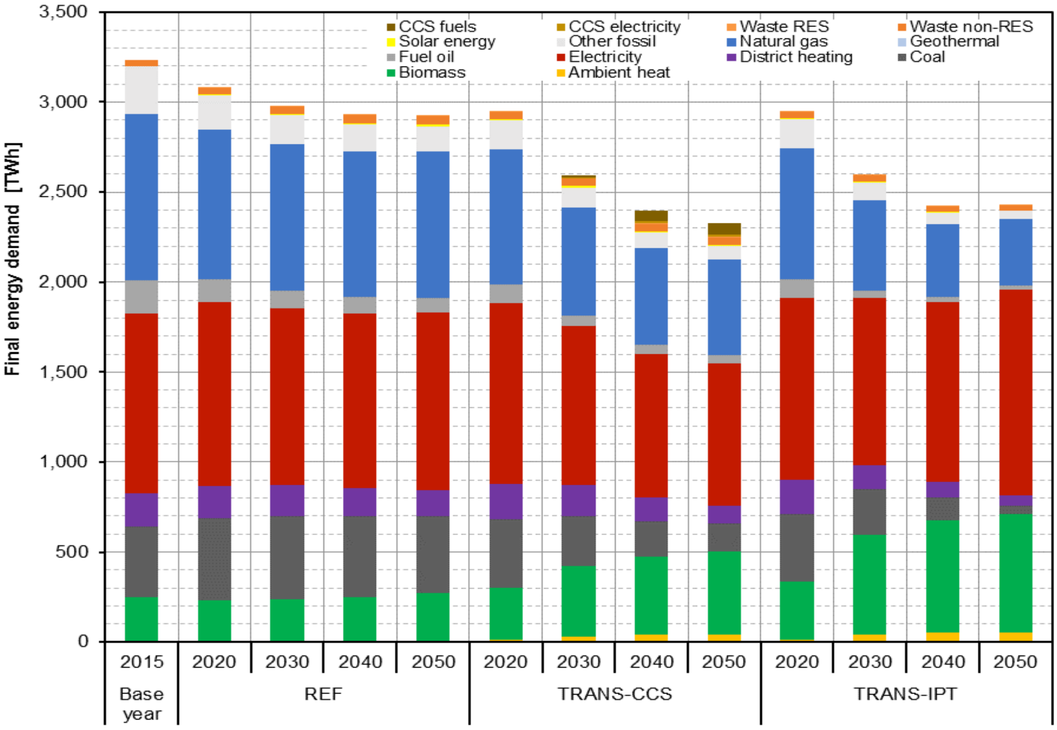

Figure 5. EU 28 final energy demand by energy carrier and scenario (2015–2050).

drastic changes in some technology fields and reach an emission reduction of around 70 % compared to 2015. In the TRANS scenarios a lot more biomass and electricity is used while coal loses significance. The additional use of electricity comes from heat generation (power-to-heat), CCS for large point sources (TRANS-CCS) and on-site hydrogen generation and electrification (TRANS-IPT) in the transition scenarios. Compared to 2015, energy demand falls by 9 % in the REF scenario and by 28 % in the TRANS-CCS and by 17 % in the TRANS-IPT scenario until 2050. Thus, even in an ambitious transition scenario, the industrial sector still consumes substantial amounts of energy and additional mitigation strategies are required. However, today's policies are not on the right track towards decarbonisation, although a slow but continuous decrease of industrial CO_2 emissions is expected in the EU28 up to 2030 and 2050. The shown transition scenarios consider a variety of different mitigation options from fuel switch, energy efficiency improvements and CCS to very innovative production processes.

To achieve the assumed exploitation of energy efficiency potentials a lot more ambitious policies than implemented today will be needed. For energy-intensive processes, new production processes need to enter the market and achieve relatively high shares by 2050. These include others low-carbon cement types, renewable hydrogen based steel, ammonia and methanol production, and electrification of glass furnaces. This assumption contains high uncertainty, because its success will depend on the technological progress in the coming years as many of these new process technologies are currently only tested on pilot-stage. The same uncertainties are true for carbon capture and storage which is currently being discussed very controversially and whose public acceptance in the future is unclear. In addition, the industry sector is committed to refurbishment-cycles of around 20 years and more, facing large uncertainties concerning future CO_2-prices. As a consequence the sector will probably not invest in CCS or innovative process technologies as long as there is not more long-term clarity and certainty concerning future CO_2 prices. In the context of a highly uncertain environment and large potential investments, public RD&I support can play an important role in accelerating the market introduction of innovative low-carbon processes. But also CO_2 emitters outside the ETS need incentives to switch to renewable or low-carbon fuels for heat generation. A CO_2 tax as the central element of a broader energy tax reform could provide the incentives needed for fuel switching. Also downstream efforts boosting material efficiency and a circular economy will need a broad policy mix (e.g. re-evaluation of VAT to the carbon-footprint of products, evaluate regulatory framework e.g. in construction to allow sustainable building products and more efficient (re-use), etc.). In general, it is necessary to set incentives towards low-carbon technologies as early as possible to accelerate the market entry of innovative processes as increases of CO_2 prices take place after 2040 and consequently affect only a small share of investment decisions taken.

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